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CONSIDERATIONS OF THE RENDEZVOUS PROBLEMS

FOR SPACE VEHICLES

By John C. Houbolt (1960)

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## SUMMARY

The problems involved in making a soft rendezvous in space are considered, as in the transfer of personnel or supplies from a ferry vehicle to a space station. The various phases of a complete rendezvous mission, such as the injection, approach, terminal, and acquisition phases, are brought out. Special attention is given to the penalties that arise due to errors in such quantities as velocity, altitude, orbital inclination, etc., and on schemes for correcting flight paths so as to use a minimum of fuel. Attention is also focused on the wait time that is involved before a rendezvous launch can be made. Wait periods of many days appear necessary if launch is to be made into the correct orbital plane, with a subsequent lead or lag correction, but wait periods of only about a day or two are feasible if launch is made into an incorrect orbital plane with a subsequent plane correction.

## INTRODUCTION

This paper is concerned with the problem of rendezvous in space, involving, for example, the ascent of a satellite or space ferry so as to make a soft contact with another satellite or space station already in orbit. The primary aims of the study are to evaluate fuel consumption

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levels that are associated with the various corrective maneuvers, and to determine the times that are suitable for initiating the rendezvous operation. See references 1 to 8 for related studies. Before giving results on these two aspects, a review is made of the various elements of a rendezvous operation.

## RENDEZVOUS PHASES

Figure 1 depicts the phases of rendezvous that would be involved in launching a space ferry from the earth's surface so as to make contact with an orbiting space station. In the injection phase the intent is to place the ascending vehicle as close as possible to the space station. During the approach major corrections are made, and may involve one or more orbital revolutions. With precise injection these two phases may be regarded as one, as shown in the lower left sketch (studies, not conjecture, are warranted to ascertain just how good injection can be made). The terminal phase is the final phase of closing, and may involve from a fraction up to a complete orbital revolution. During this phase the pilot of a manned vehicle may actually be "driving" his craft to the station. The docking or acquisition phase involves the actual "soft" contact - the securing of lines, air locks, etc.

## CORRECTIVE MEASURES

Position errors.- The five basic errors that may arise in rendezvous operation are shown in figure 2. The injected vehicle may lead or lag, be above or below, or be to one side of the target or station (the latter being given by the incorrect orbital plane sketch). In addition, the speeds may be different and the velocity vectors may not be parallel, as would be the case if the ferry assumed a different orbit than that generated by the station (orbital axis misalinement).

Correction procedures.- In general, corrections are made through use of Hohmann type transfer orbits. Three corrective procedures are illustrated in figure 3, where a circular orbit of the target or space station is assumed. In the lead case, the ferry is first given a forward impulse to throw it into an elliptical orbit having a period just sufficiently greater than the circular orbit so that after a given number of revolutions the ferry and station are coincident; a reverse thrust of magnitude equal to the forward impulse is then given to restore speed compatibility.

One type of altitude correction is shown in the center of the figure. For the case of the ferry above, a reverse thrust is first given, then a coast for half a revolution, another reverse thrust, a half revolution coast, and finally a forward thrust.

For the change in plane case, the basic correction is to give the vehicle a side thrust at either nodal point. Because of the high forward velocities usually involved, this correction is quite costly fuelwise. There are other more refined ways of making this correction at a slight savings in fuel, see, for example, reference 8, but it is not necessary to consider these methods in detail here.

Fuel used.- On the right of figure 3 is a listing of the fuel consumed, where $\Delta m/m$ represents the ratio of fuel mass used to total vehicle mass. In the lead or lag case, each impulse requires half the amount of fuel indicated by the equations; n refers to the number of complete revolutions that are allotted to complete the correction. The second equation given for this case may be associated with an injection that timewise was ahead of or behind the zero launch time by an amount t, and follows from the relation $\theta_{rad} = \frac{Vt}{r}$. All the $\frac{\Delta m}{m}$ equations shown on the slide were derived on the basis of an approximate 400-mile-altitude orbit and for a specific impulse on the corrective rockets of 250. These equations may all be deduced from the generalized relations that are shown in figure 4, which follow from the well-known two-body orbit equations and the equation for an idealized burning rocket.

It is instructive to establish limits on errors by specifying a certain amount of fuel consumption. For a choice of $\frac{\Delta m}{m} = 0.01$ the following limits are found (again for $r = 4{,}400$ miles)

$$\theta = 1.84^{\circ}$$

$$h = 11.3 \text{ miles}$$

$$\gamma = 0.182^{\circ}$$

The above errors, while discussed separately, may of course occur in combination. Figure 5 is a result which treats some of the errors in combination, and applies to a choice of $\frac{\Delta m}{m} = 0.01$. Thus, the surface of the volumes shown in this figure represents combination of errors which will require a 1-percent fuel utilization (1 percent of total vehicle mass). In this figure $s$ is lead or lag in miles, $s = \theta r$. Note that for clarity only two quadrants of the highly distorted volume are shown. Note also how the presence of a relative velocity improves tolerable limits for positive $s$ but greatly decreases the limits for negative $s$; this finding reflects the fact that when errors are treated in combinations, some of the corrective measures work favorably together, whereas others are in conflict.

The figure is of value since it gives one a feel of how much error can be tolerated for a given amount of fuel consumption. The value of $\frac{\Delta m}{m} = 0.01$ is a convenient choice since errors for other fuel consumptions may be found easily by proportion (for the lower percentages only). Thus, for $\frac{\Delta m}{m} = 0.02$, the tolerable errors are double those shown in figure 5.

## SUITABLE LAUNCH TIMES

The determination of suitable times to launch a ferry vehicle to make rendezvous with an orbiting station without requiring excessive fuel for corrective measures poses a very critical problem. It is important to point out that the corrections referred to here are not only the inadvertent errors that arise in the ascent phase, as discussed earlier in the report, but rather also include the errors that cannot be avoided because the geometry is not just right at the time of launch. Thus, the errors discussed in this section are mainly those which are of the predictable geometric type, and hence represent in effect the lower limit of correction necessary.

Two means for determining suitable launch time are pursued. One is to launch into the correct orbital plane (the plane of the target) and accept the lead or lag error as the error to be corrected, figure 6(a). The other is to launch the ferry adjacent to the space station (aiming for no lead or lag error), accepting and then adjusting for the incorrect orbital plane, figure 6(b).

Launch into correct orbital plane.- Assume the space station to be orbiting around the earth in a fixed orbital plane; that is, assume for the moment that the plane is without precession. The launch site will cross this orbital plane twice every revolution of the earth, and after N complete revolutions of the earth (from the time of original launch of the space station), the space station itself will have revolved an amount given by

$$N \frac{T_e}{T_s} = n \pm \frac{\theta}{2\pi} \tag{1}$$

where $T_e$ is the period of revolution of the earth; $T_s$, the station orbital period; n, the nearest whole number representing space station revolutions; and $\frac{\theta}{2\pi}$, the fraction of a revolution relative to this whole number which pinpoints the exact location of the space station. (Note precessional effects may be taken into account by choosing an appropriate effective value of $T_e/T_s$, but since the point to be made can be demonstrated without taking these effects into account, they will be neglected herein.) In effect, then, $\theta$ is the amount of lead or lag (see figs. 2, 3, and 6(a)) that must be made up by the rendezvous corrective procedures.

Now an upper limit on $\theta$ can be established by stipulating the maximum amount of fuel that can be used to make up this lag or lead correction. Thus, take the example of $\frac{\Delta m}{m} = 0.02$; from the equation in figure 3 this fixes $\theta$ as approximately $3.6^{\circ}$ or $\left(\frac{\theta}{2\pi}\right)_{max} = 0.01$. In terms of $t$ this limit corresponds to $t_{max}$ of approximately 1 minute. As regards suitable launch times to make rendezvous without exceeding $\frac{\Delta m}{m} = 0.02$, equation (1), which in the theory of numbers is referred to as a Diophantine equation, is now examined to determine the combinations of $n$ and $N$ which will lead to an $\theta/2\pi$ less than 0.01. In table I this procedure is demonstrated for three assumed orbital periods and for $N$ through 40. Examination of the columns indicates that the first day suitable for launch so as to not exceed $\frac{\theta}{2\pi} = 0.01$ is the 35th day for $T_s = 101$, 37th for $T_s = 101.1$, and that there are none at all in the first 40 days for $T_s = 101.2$. These and other results are shown in figure 7. The timewise tolerance of 1 minute or less on the left sketch applies to a $\frac{\Delta m}{m} < 0.02$, whereas the right sketch for 2 minutes or less applied for an assumed maximum fuel usage of $\frac{\Delta m}{m} < 0.04$.

It might be thought that the consideration of the second orbital crossing might decrease the wait period. Results for this case are shown in figure 8 for a 1-minute maximum leeway, which as before corresponds to $\frac{\Delta m}{m} < 0.02$. There is no apparent improvement in decreasing the number of wait days.

These figures show that to initiate a rendezvous operation by launching into the correct orbital plane in general involves excessively long wait periods, if the amount of fuel that will be required for corrective measures is to be kept within reasonable limits. Special cases can of course be derived which allow a launch to be made once or twice each day. For example, if the ratio $T_e/T_s$ in equation (1) is some whole number, then there will be no $\theta$, and launch can be made at least once every day. This situation is akin to the rendezvous compatible orbits treated in reference 5. Just how realistic it is to make $T_e/T_s$ a whole number, which remains so with time, is an important question requiring evaluation.

Adjacent launching technique.- Assume the situation where the space station is to pass in the proximity of a point overhead of the launching site, and consider the ferry to be launched so that at the end of injection it is adjacent (opposite) the space station, travelling roughly parallel, but in general in a different orbital plane. The intent then is to change to the correct orbital plane when the ferry arrives at the nodal point of the two planes. With reference to figure 9 let

$$\bar{a} = -j \sin \alpha_s + k \cos \alpha_s \tag{2}$$

be a unit vector perpendicular to the orbital plane of the space station, where $\alpha_s$ is the plane inclination. Point I is considered the injection point of the ferry, which is as close to the orbital plane of the station as can be obtained under the condition of adjacency; this point is located by

$$\left.\begin{aligned} x &= r \cos\alpha \sin\theta \\ y &= r \cos\alpha \cos\theta \\ z &= r \sin\alpha \end{aligned}\right\} \tag{3}$$

A plane passing through I and the center of the earth is sought which intersects the orbital plane of the space station at a minimum angle, this minimum being desired so that the fuel expenditure at correction is the least. The vector defining this plane will be perpendicular to $\bar{r}$ and by inspection will make a minimum angle with $\bar{a}$ when it lies in the plane of $\bar{a}$ and $\bar{r}$. The plane of $\bar{a}$ and $\bar{r}$ is defined by the vector $\bar{b}$, given by

$$\bar{b} = \bar{r} x \bar{a} = i(y \cos\alpha_s + z \sin\alpha_s) - jx \cos\alpha_s - kx \sin\alpha_s \tag{4}$$

The vector defining the plane sought for the ferry is now found as

$$\begin{aligned} \bar{c} = \bar{b} x \bar{r} = {} & i(-xz \cos\alpha_s + xy \sin\alpha_s) + j(-x^2 \sin\alpha_s - yz \cos\alpha_s \\ & - z^2 \sin\alpha_s) + k(y^2 \cos\alpha_s + yz \sin\alpha_s + x^2 \cos\alpha_s) \end{aligned} \tag{5}$$

The minimum angle $\gamma$ between the two orbital planes is then defined by

$$\cos\gamma = \frac{a_x c_x + a_y c_y + a_z c_z}{|a|\,|c|} \tag{6}$$

By equations (2) and (5), this equation yields

$$\sin \gamma = \sin \alpha \cos \alpha_s - \cos \alpha \sin \alpha_s \cos \theta \tag{7}$$

The orbital plane of the ferry intersects that of the space station along the vector $\bar{b}$; the angular positions of this nodal line, figure 9(b), are given by

$$\tan \theta_n = \frac{x_n}{y_n}$$

$$\frac{\tan \alpha_n}{\cos \theta_n} = \frac{z_n}{y_n}$$

which, through the application of equations (3) to the nodal point n, lead to

$$\tan \theta_n = - \frac{1}{\tan \theta} - \frac{\tan \alpha \tan \alpha_s}{\sin \theta} \tag{8a}$$

$$\tan \alpha_n = \cos \theta_n \tan \alpha_s \tag{8b}$$

The intersection of ferry orbital plane with the x-y plane and the actual inclination relative to the x-y plane are given by

$$y = - \frac{c_x}{c_y} x \tag{9a}$$

$$\cos \alpha_f = \frac{c_z}{|c|} \tag{9b}$$

The conditions for adjacency may now be found as follows, see figure 9(b). At $\theta_s$ the space station was launched into an orbit inclination $\alpha_s$, and it is assumed that $\alpha$ at injection was the same as it is for the ferry (that is, both station and ferry are launched from the same site and follow similar trajectories); the relation between $\theta_s$, $\alpha$, and $\alpha_s$ is

$$\cos \theta_s = \frac{\tan \alpha}{\tan \alpha_s} \tag{10}$$

Then afterwards, at injection of the ferry, adjacency with the space station may be defined by the equation

$$\left(N \pm \frac{\Delta\theta}{2\pi}\right)\frac{T_e}{T_s} = n \pm \frac{\Delta\beta}{2\pi} \tag{11}$$

where $N$ is the number of earth revolutions to the nearest whole number from the time of space station launch, $\Delta\theta = \theta - \theta_s$ is the azimuth angle at time of adjacency relative to original space station launch azimuth, $T_e$ and $T_s$ are as before, $n$ is the number of space station revolutions to the nearest whole number, and $\Delta\beta = \beta - \beta_s$, where $\beta$ is orbit arc of ferry from point of adjacency to nodal point and $\beta_s$ is orbit arc of the station from its injection point to nodal point. By spherical trigonometry $\beta$ and $\beta_s$ can be shown to be defined by

$$\cos \beta = \sin \alpha \sin \alpha_n + \cos \alpha \cos \alpha_n \cos(\theta + \theta_n) \tag{12a}$$

$$\cos\beta_s = \sin\alpha\sin\alpha_n + \cos\alpha\cos\alpha_n\cos(\theta_s + \theta_n) \tag{12b}$$

Equations (8), (10), (11), and (12), together with the definition of $\Delta\theta$ and $\Delta\beta$, can now be solved for the desired angle $\theta$ at which adjacency of the space station and ferry occurs. (Note, one procedure is as follows: from equation (10) $\alpha_s$ is determined. With this $\alpha_s$ and an assumed $\theta$, equations (8) are solved for $\theta_n$ and $\alpha_n$. Then equations (12) may be solved for $\beta$ and $\beta_s$, so that $\Delta\beta$ is found. This $\Delta\beta$ is tested in equation (11). If the equation is not satisfied, a different $\theta$ is assumed and the process repeated until a $\theta$ is found which causes equation (11) to be satisfied. Note also that in this solution $N$ is chosen and $n$ is varied so as to yield the smallest value of $\theta$.) With $\theta$ established, equation (7) is used to determine the correction angle $\gamma$ that will be necessary.

In the use of these equations, study has shown that by far the best conditions from a rendezvous point of view are to make $\theta_s = 0$ and $\alpha_s = \alpha$. Thus, attention will be focused mainly on this case. Further, in making this treatment the point of view will be shifted to that of determining the amount of fuel that must be expended to make a rendezvous once a day, rather than to specify the amount of fuel and then to determine how many days of wait are necessary before conditions are right, as was done in the previous section.

Results for the specific case of $\theta_s = 0$, $\alpha_s = \alpha$, and $\frac{T_e}{T_s} = \frac{1440}{101}$ are given in figure 10 for $\alpha$ up to $40^{\circ}$. For the first day $\Delta m/m$ is in the order of 0.01 or less. For the second day the ratio is higher but still only reaches 0.04. On the third day the ratio is again less than 0.01 and on the fourth day virtually no fuel is needed for corrective purposes. On successive days thereafter there appears to be a repetition of the pattern. The remarkable improvement of this technique for performing rendezvous over the technique given in the previous section is demonstrated by this figure.

For the case of $\alpha_s = \alpha$ and small values of $\alpha$, $(\cos \alpha \approx 1)$, the above equations reduce to a very simple form. Equation (7) becomes

$$\begin{aligned} \gamma &= \sin \alpha \cos \alpha(1 - \cos \theta) \\ &= \frac{\theta^2}{2} \sin \alpha \cos \alpha \end{aligned}$$

and equation (12) yields (taking $\Delta\beta = \Delta\theta = \theta$)

$$\theta_{rad} = 2\pi \frac{N \frac{T_e}{T_s} - n}{\pm\left(\frac{T_e}{T_s} - 1\right)}$$

These equations give

$$\gamma^{o} = 360\pi\left(\frac{N \frac{T_e}{T_s} - n}{\frac{T_e}{T_s} - 1}\right)^2 \sin \alpha \cos \alpha \qquad (13)$$

which in turn leads to

$$\frac{\Delta m}{m} = \frac{360\pi v_o}{u}\left(\frac{N\frac{T_e}{T_s} - n}{\frac{T_e}{T_s} - 1}\right)^2 \sin\alpha\cos\alpha \tag{14}$$

To give some indication of the influence of $\alpha_s \neq \alpha$, equation (7) was used in conjunction with equation (10) and $\Delta\theta = \theta - \theta_s$ to determine the values of $\Delta\theta$ which satisfy these equations for a choice of $\gamma = 0.4^\circ$ $\left(\text{which corresponds to a fuel consumption of } \frac{\Delta m}{m} = 0.02\right)$. Results are shown in figure 11. The meaning of this figure is that it must be possible to inject the ferry adjacent to the space station so that the $\Delta\theta$ for this adjacency does not exceed the $\Delta\theta$ shown, otherwise the fuel expenditure will be greater than $\Delta m = 0.02m$. It is noted that there is a very pronounced dropoff in $\Delta\theta$ as $\alpha$ is reduced slightly from $\alpha_s$. The encounter of low $\Delta\theta$ would mean that several days may have to be passed before a condition of adjacency is established within this low $\Delta\theta$ value. Thus, the use of low values of $\alpha$ relative to $\alpha_s$ tends to produce long wait days as was the case in the previous section.

## CONCLUDING REMARKS

Other ways are available to beat the long wait periods for suitable rendezvous days, but rather strong conditions are usually attached. The compatible rendezvous orbits method mentioned in the text is one such method; in this case the period must be controlled precisely. Other schemes would involve the use of multiple launching sites, equatorial launching and equatorial orbits, or polar launchings and polar orbits.

The main idea in this report, however, was to see if rendezvous would be performed at reasonably close frequencies in the face of existing launch bases and arbitrary orbit periods. The planned launch in a mismatched orbital plane so as to have adjacency with respect to forward motion, and then correcting the orbital plane later, appears to be a good way to approach the rendezvous problem. The procedure of course has the disadvantage that the entire vehicle must be swung around normal to its flight direction so that a side impulse can be given.

The change in plane technique also offers the possibility that the ferry may be launched so that when it crosses the space station orbital plane it is not yet up to orbital velocity. An impulse of such a nature would then be given at this point to not only correct the orbital plane but to bring the ferry up to the desired speed, with the results that this combined correction may save some fuel relative to the cases where corrections are made separately.

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TABLE I.- SOLUTION OF EQUATION (1)

| $T_e/T_s$ = | $\frac{1440}{101}$ | $\frac{1440}{101.1}$ | $\frac{1440}{101.2}$ |
|---|---|---|---|
| N | $n \pm \frac{\theta}{2\pi}$ | $n \pm \frac{\theta}{2\pi}$ | $n \pm \frac{\theta}{2\pi}$ |
| 1 | 14 + 0.2574 | 14 + 0.2433 | 14 + 0.2292 |
| 2 | 29 - .4851 | 28 + .4866 | 28 + .4585 |
| 3 | 43 - .2277 | 43 - .2700 | 43 - .3123 |
| 4 | 57 + .0297 | 57 - .0267 | 57 - .0830 |
| 5 | 71 + .2871 | 71 + .2166 | 71 + .1462 |
| 6 | 86 - .4554 | 85 + .4599 | 85 + .3755 |
| 7 | 100 - .1980 | 100 - .2967 | 100 - .3953 |
| 8 | 114 + .0594 | 114 - .0534 | 114 - .1660 |
| 9 | 128 + .3168 | 128 + .1899 | 128 + .0632 |
| 10 | 143 - .4257 | 142 + .4332 | 142 + .2925 |
| 11 | 157 - .1683 | 157 - .3234 | 157 - .4783 |
| 12 | 171 + .0891 | 171 - .0801 | 171 - .2490 |
| 13 | 185 + .3465 | 185 + .1632 | 185 - .0198 |
| 14 | 200 - .3960 | 199 + .4065 | 199 + .2095 |
| 15 | 214 - .1386 | 214 - .3502 | 213 + .4387 |
| 16 | 228 + .1188 | 228 - .1068 | 228 - .3320 |
| 17 | 242 + .3762 | 242 + .1365 | 242 - .1028 |
| 18 | 257 - .3663 | 256 + .3798 | 256 + .1265 |
| 19 | 271 - .1089 | 271 - .3769 | 270 + .3557 |
| 20 | 285 + .1485 | 285 - .1335 | 285 - .4150 |
| 21 | 299 + .4059 | 299 + .1098 | 299 - .1858 |
| 22 | 314 - .3366 | 313 + .3531 | 313 + .0435 |
| 23 | 328 - .0792 | 328 - .4036 | 327 + .2727 |
| 24 | 342 + .1782 | 342 - .1602 | 342 - .4980 |
| 25 | 356 + .4356 | 356 + .0831 | 356 - .2688 |
| 26 | 371 - .3069 | 370 + .3264 | 370 - .0395 |
| 27 | 385 - .0495 | 385 - .4303 | 384 + .1897 |
| 28 | 399 + .2079 | 399 - .1869 | 398 + .4190 |
| 29 | 413 + .4653 | 413 + .0564 | 413 - .3518 |
| 30 | 428 - .2772 | 427 + .2997 | 427 - .1225 |
| 31 | 442 - .0198 | 442 - .4570 | 441 + .1067 |
| 32 | 456 + .2376 | 456 - .2136 | 455 + .3360 |
| 33 | 470 + .4951 | 470 + .0297 | 470 - .4348 |
| 34 | 485 - .2475 | 484 + .2730 | 484 - .2055 |
| 35 | 499 + .0099 | 499 - .4837 | 498 + .0237 |
| 36 | 513 + .2673 | 513 - .2404 | 512 + .2530 |
| 37 | 528 - .4753 | 527 + .0030 | 526 + .4822 |
| 38 | 542 - .2178 | 541 + .2463 | 541 - .2885 |
| 39 | 556 + .0396 | 555 + .4896 | 555 - .0593 |
| 40 | 570 + .2970 | 570 - .2671 | 569 + .1700 |

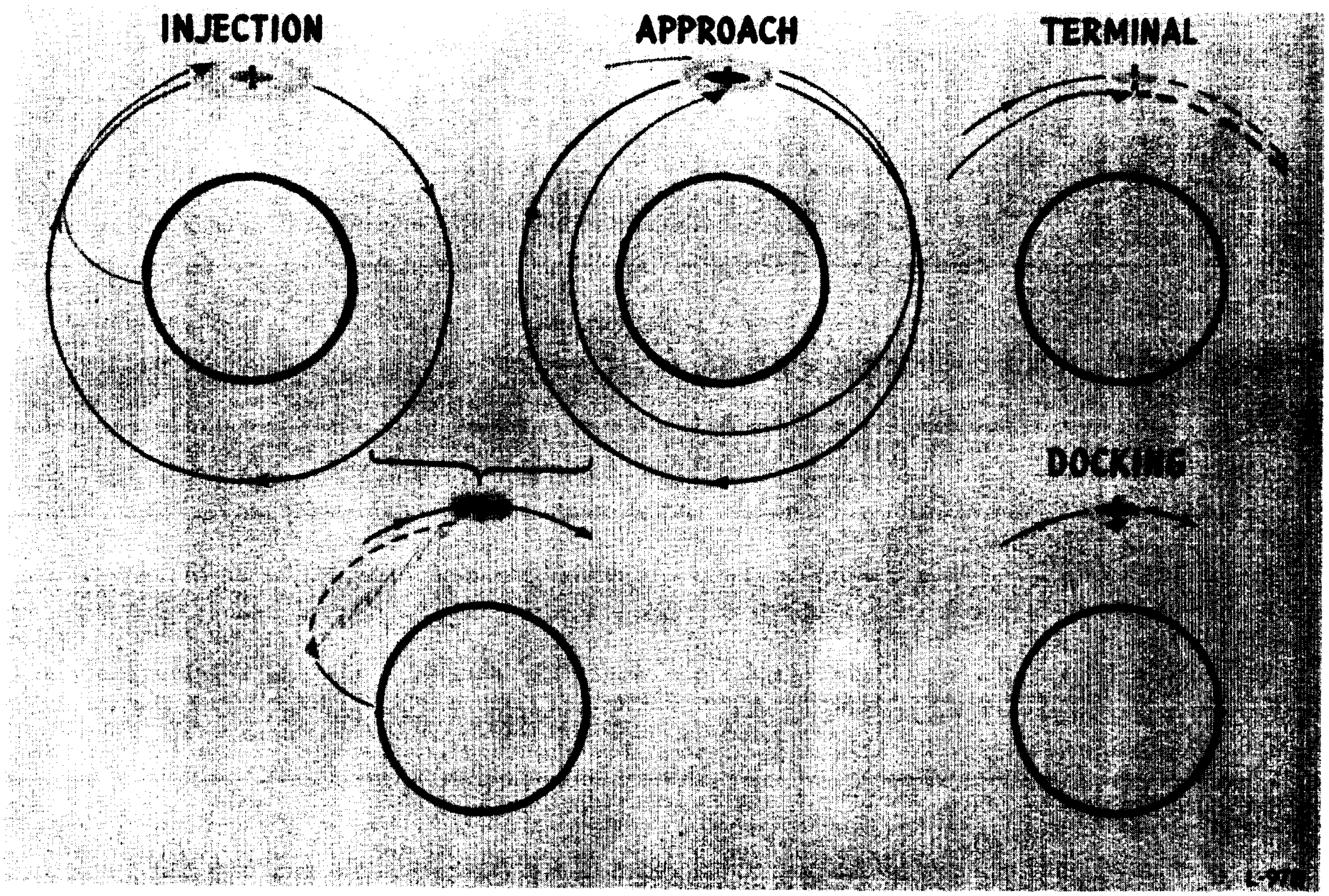


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Figure 1.- Phases of rendezvous.

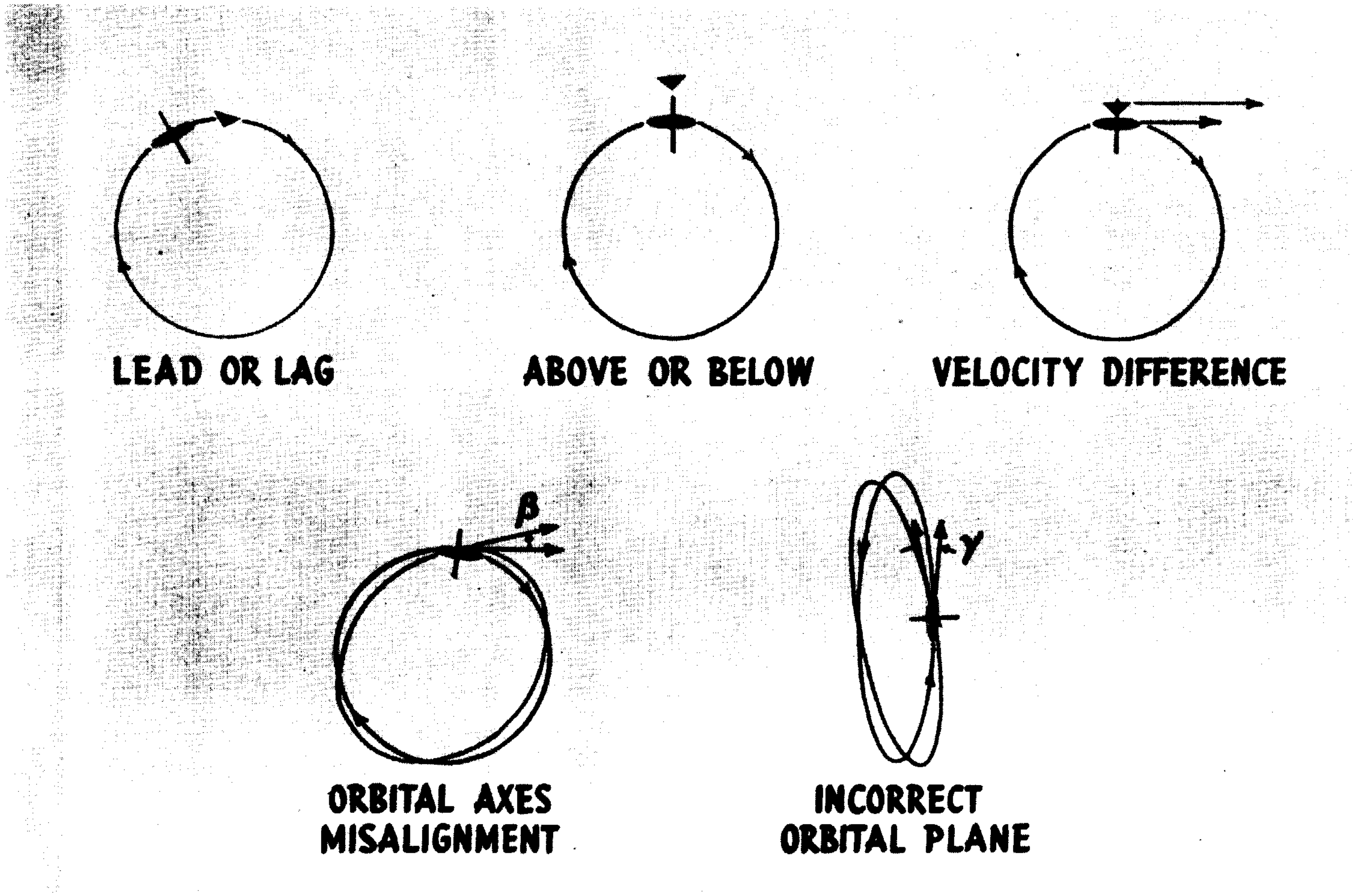


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Figure 2.- Position errors.

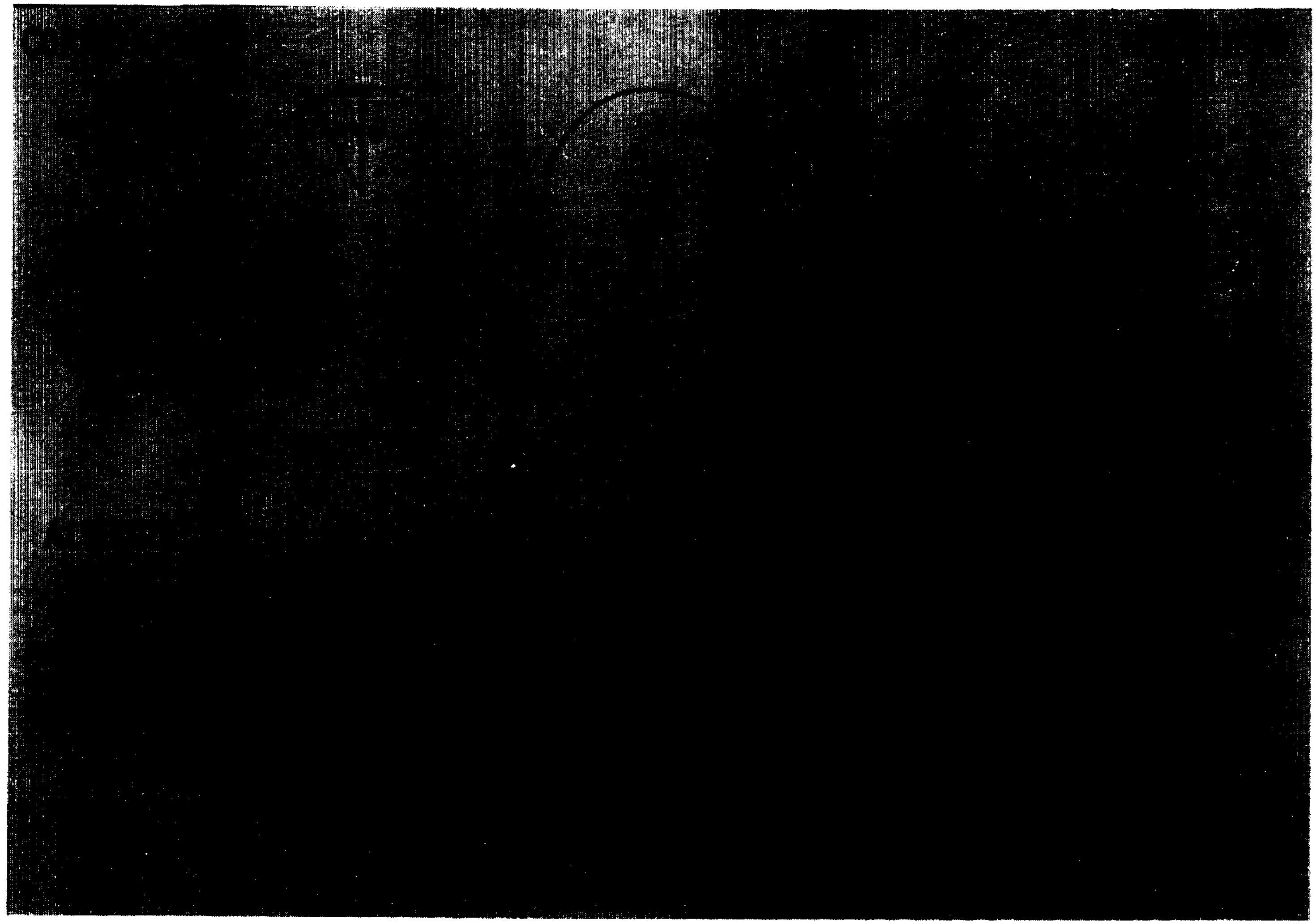

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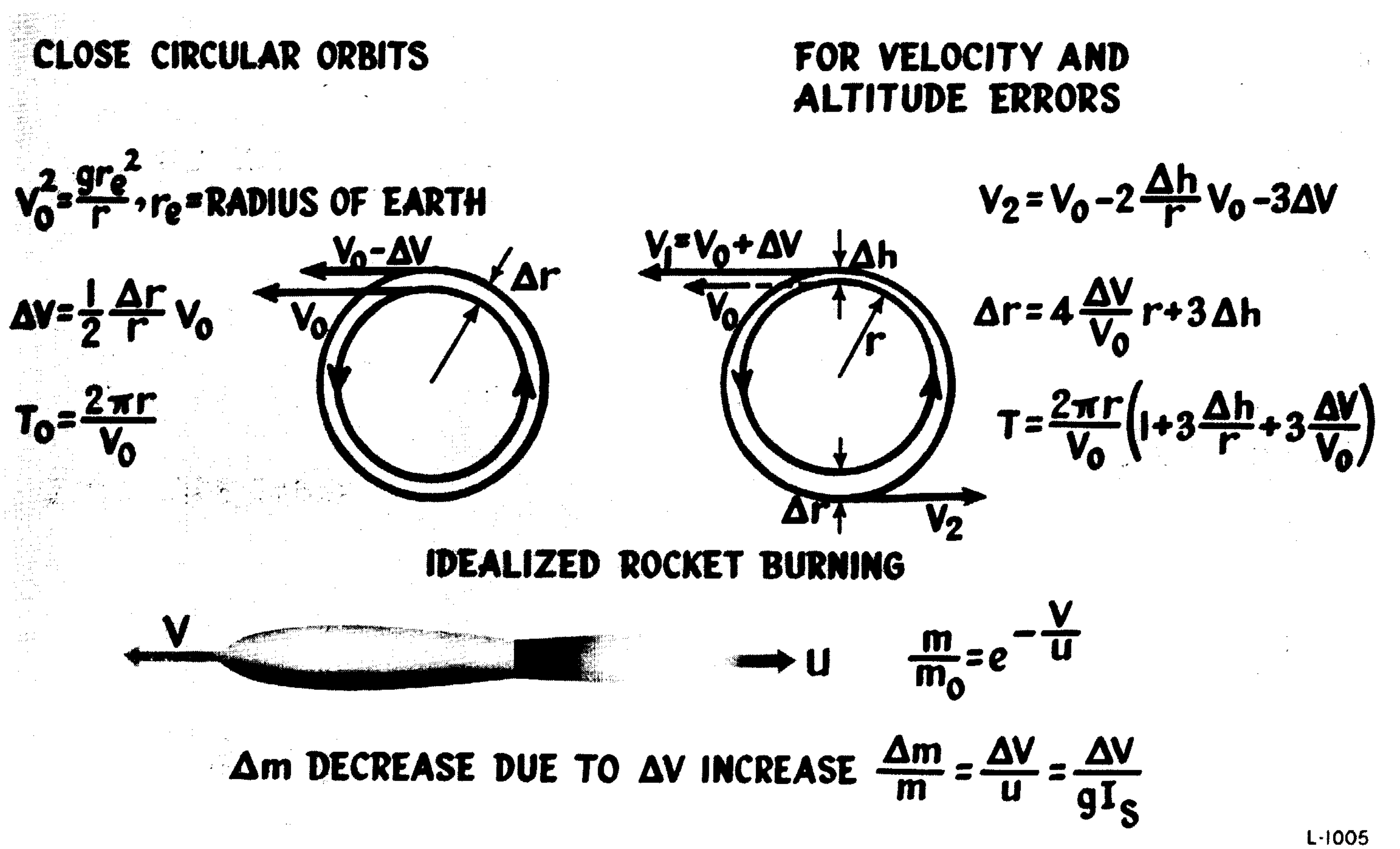
Figure 3.- Illustrative corrective measures.




(a) Orbital and rocket mechanics.

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Figure 4.- Generalized relations for use in orbit transfer studies.

(b) Impulses required.

Figure 4.- Concluded.

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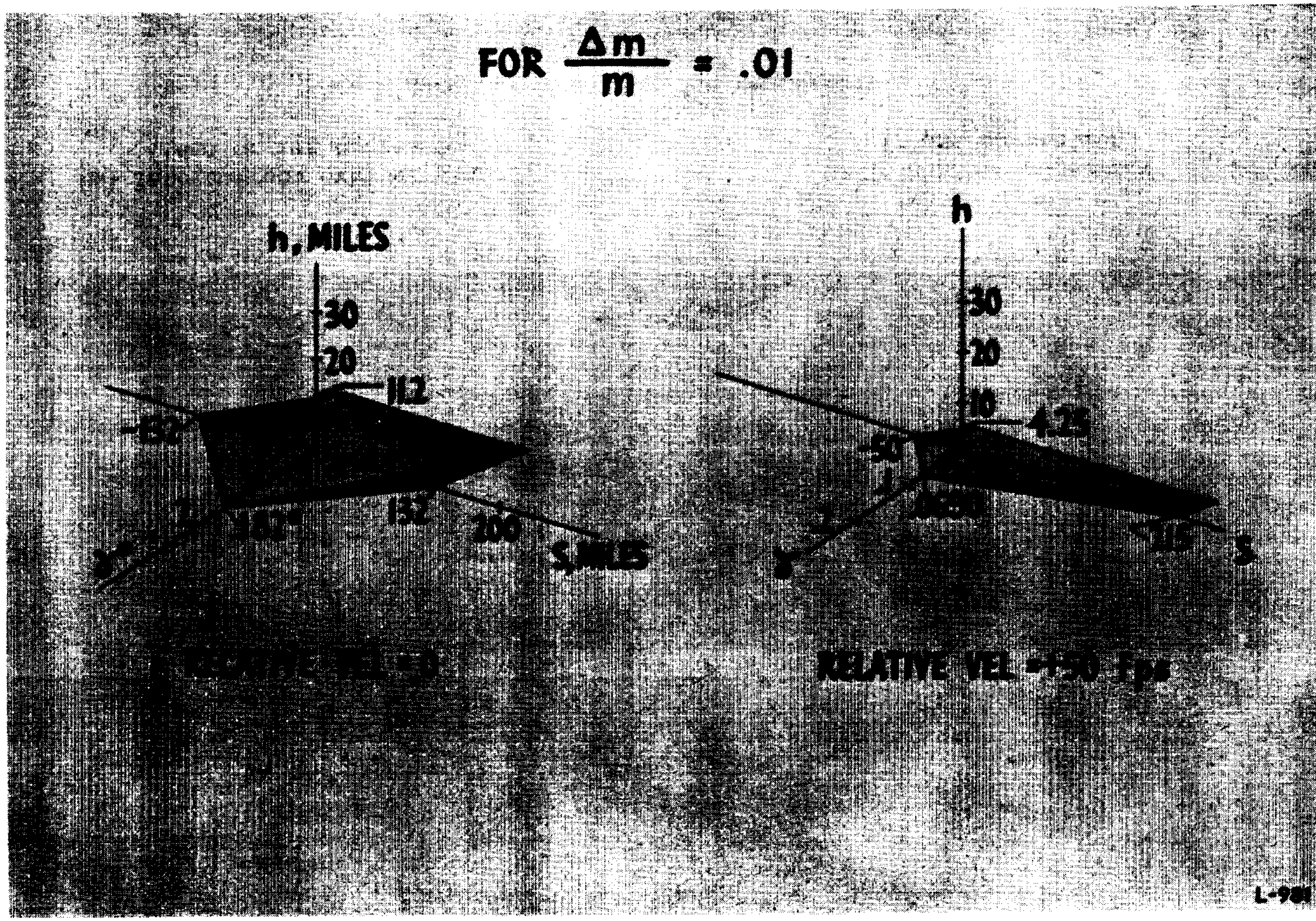


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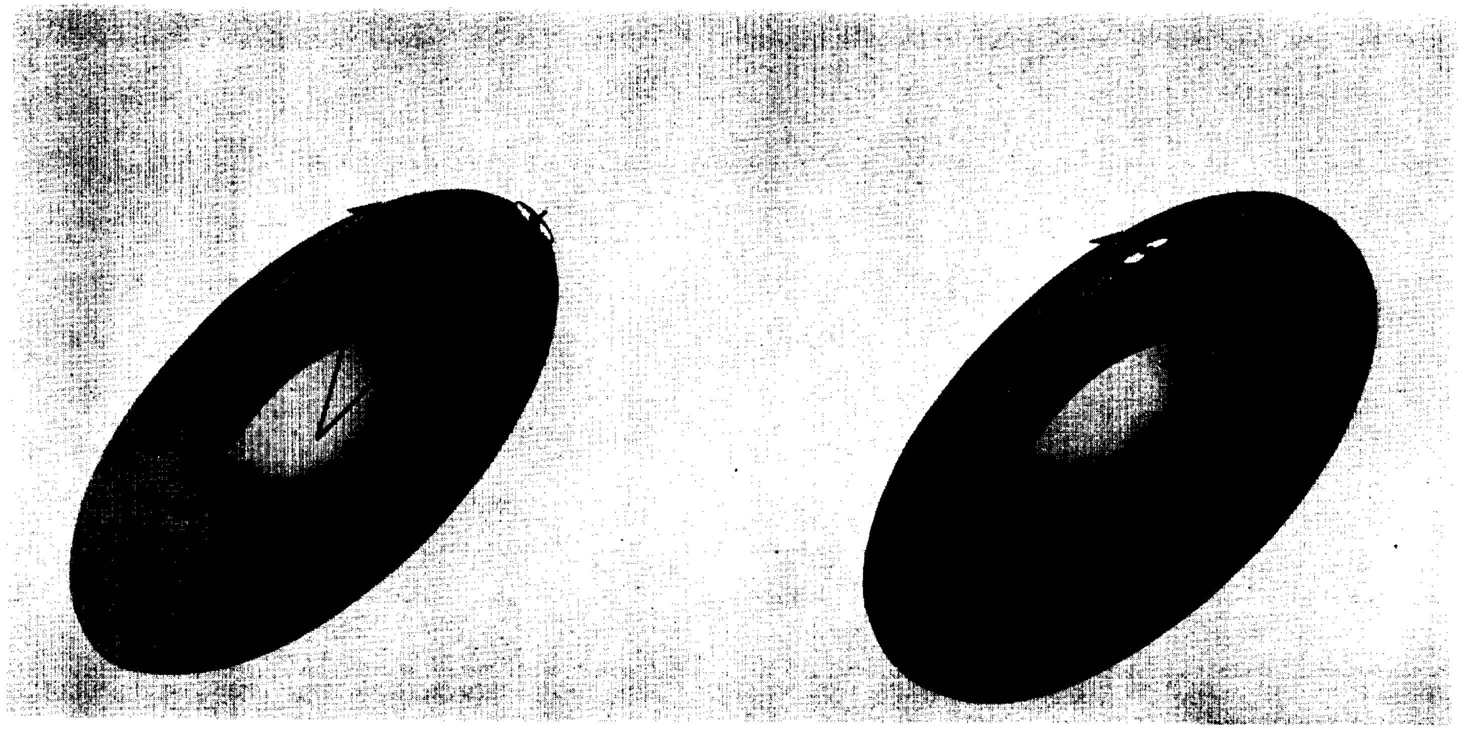
Figure 5.- "Volume" error limits.



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(a) Into correct orbital plane (lead or lag correction).

(b) To achieve adjacency (plane correction).

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Figure 6.- Launching for rendezvous.

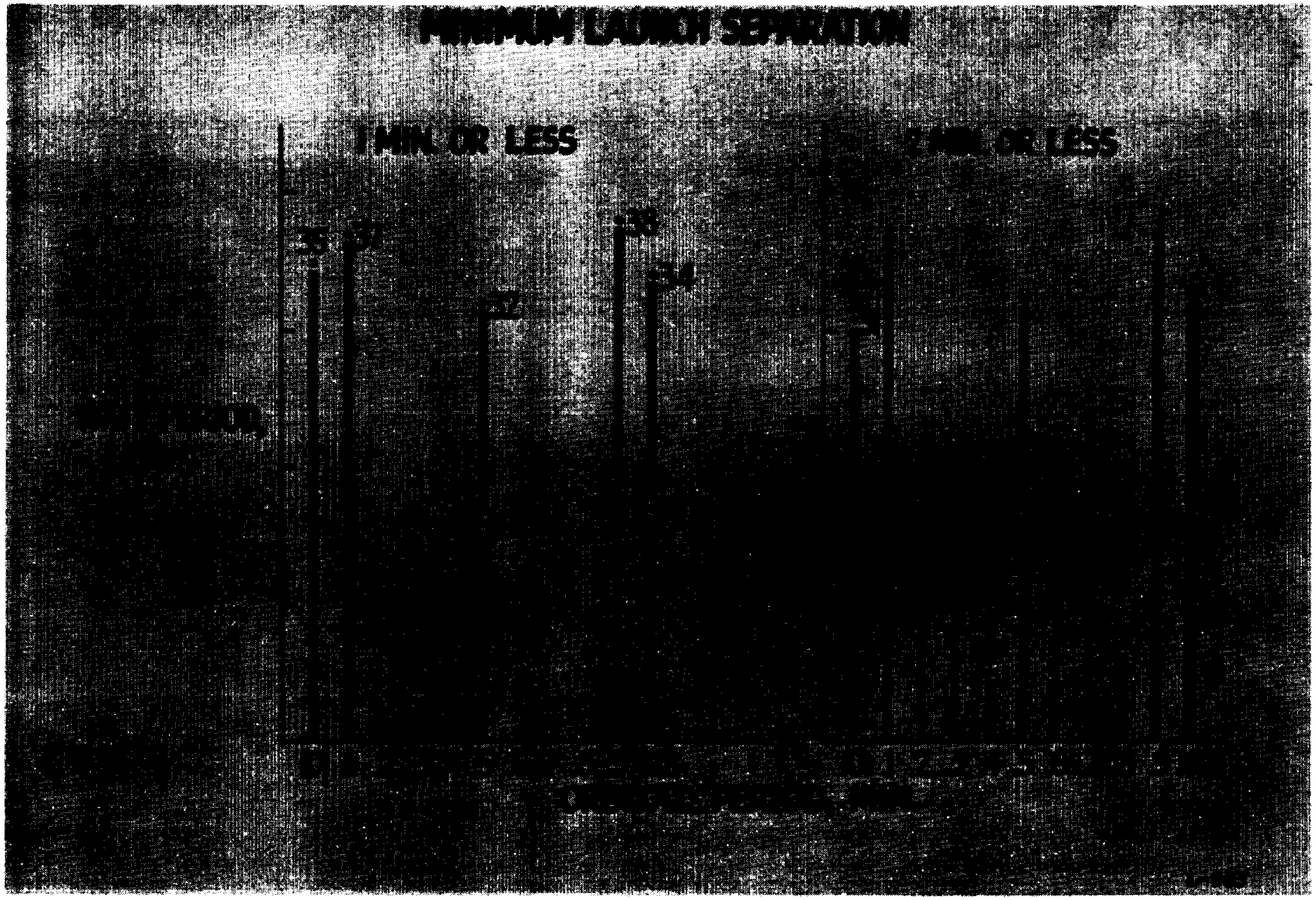


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Figure 7.- Favorable launching days.

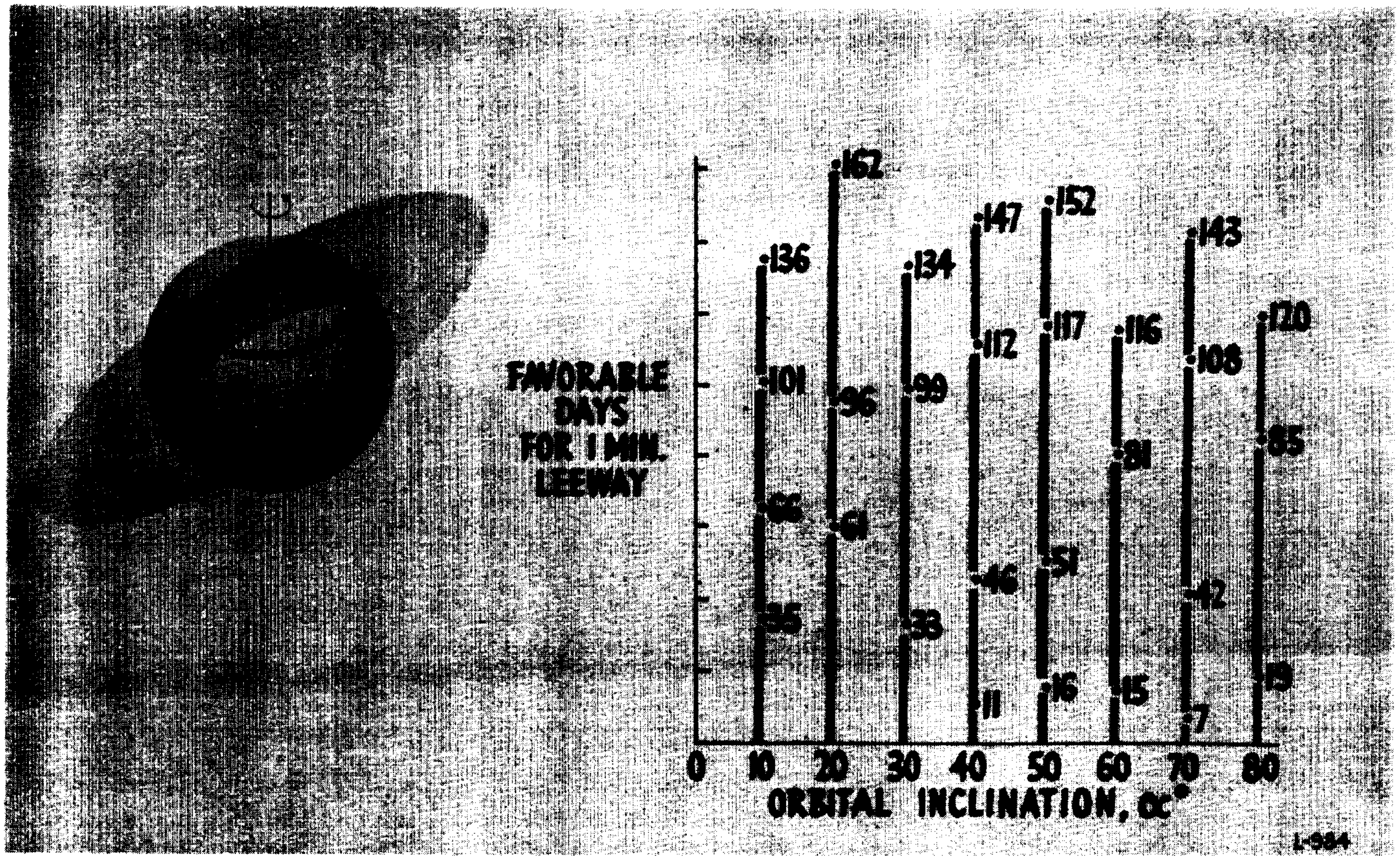


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Figure 8.- Favorable launch days at second orbital crossing for $T_S$ = 101 min., $C_L$ = 10 deg.

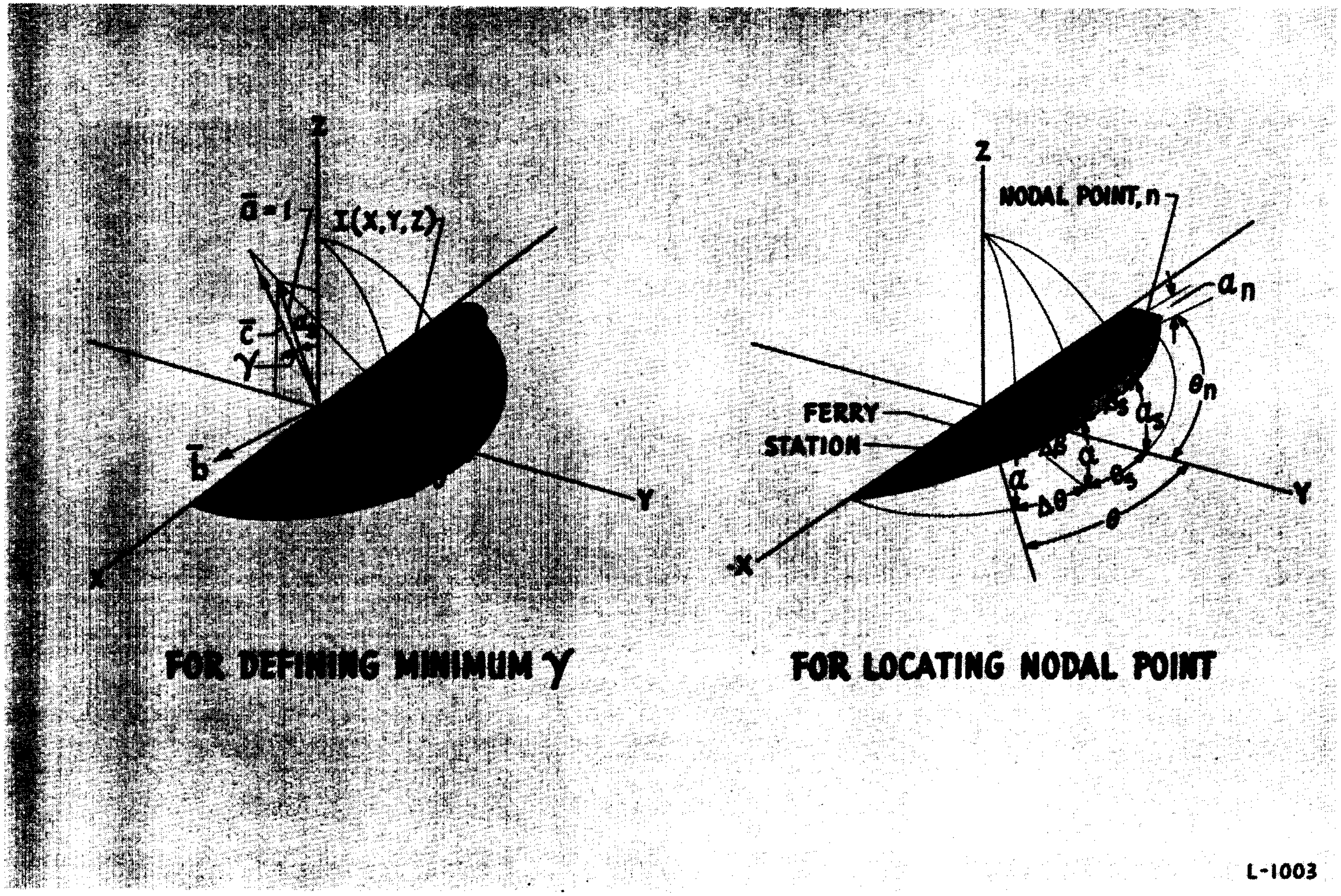


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Figure 9.- Coordinates.

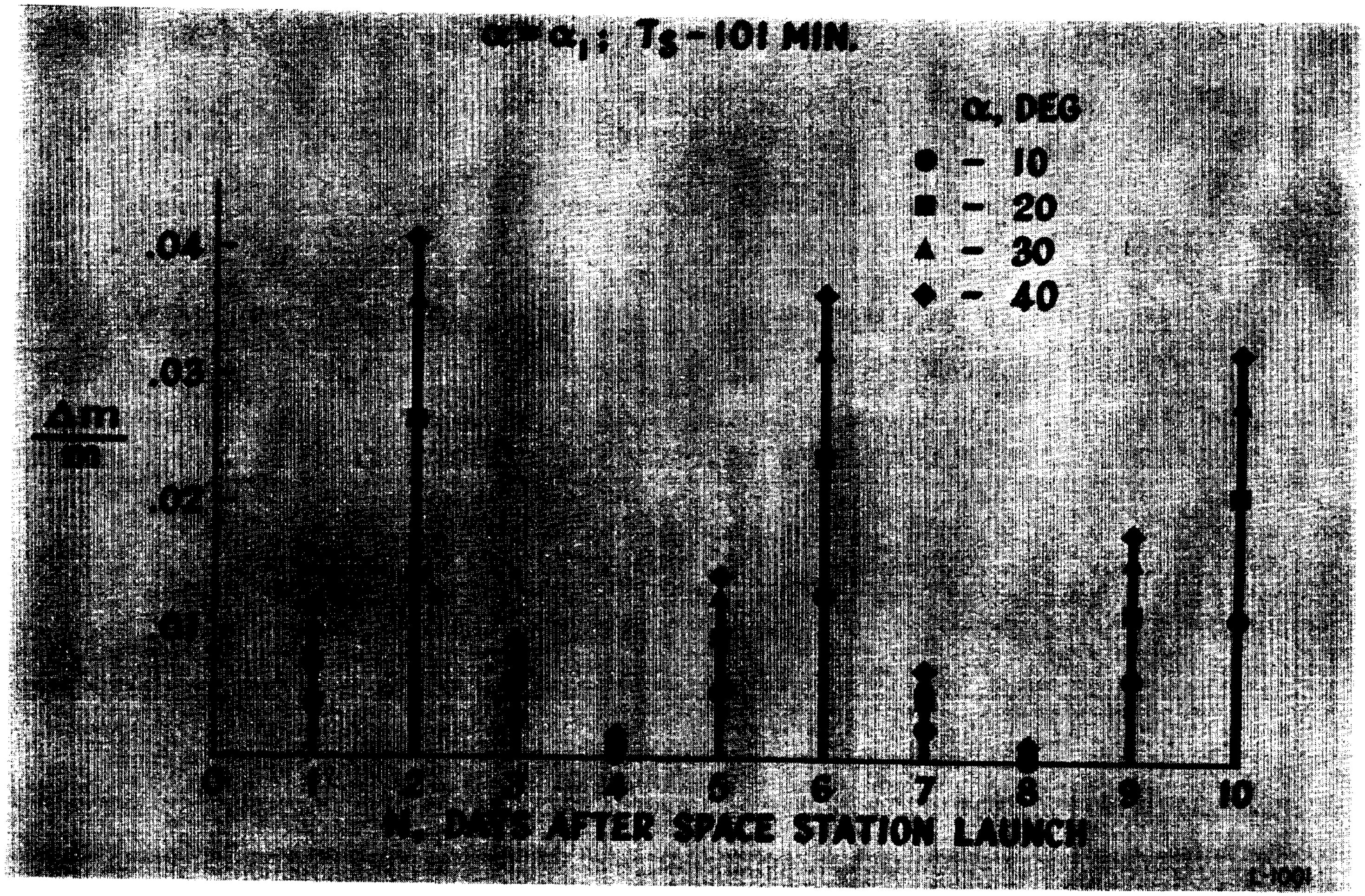


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Figure 10.- Fuel consumption for incorrect plane technique.

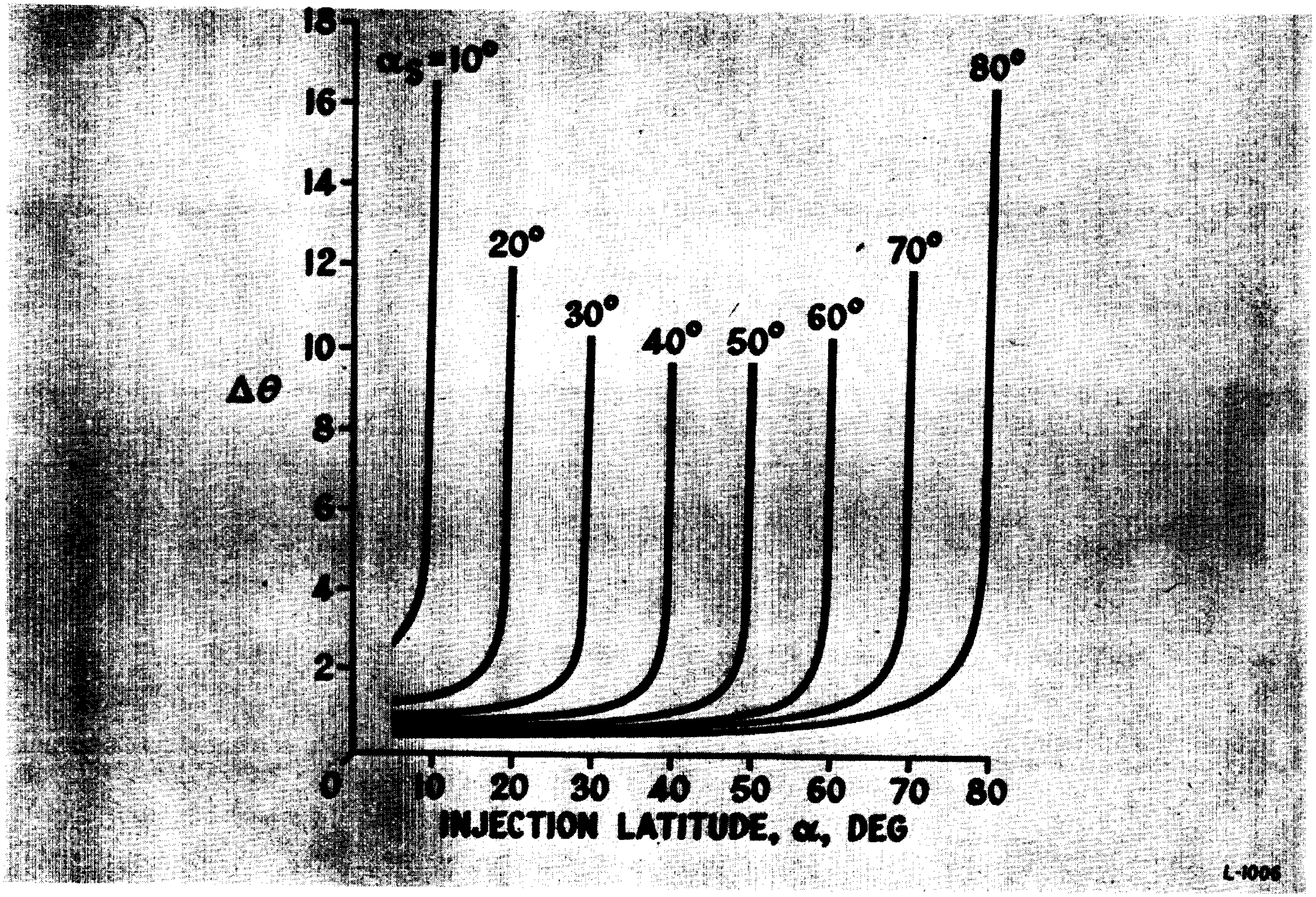


Figure 11.- Maximum $\Delta\theta$ allowed for $\Delta_m = 0.02$ in., ($\gamma = 0.4^{\circ}$).